

DISCOVERY OF HIGH-FREQUENCY QUASI-PERIODIC OSCILLATIONS IN THE BLACK-HOLE
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ABSTRACT

We report the discovery of 8.5σ high-frequency quasi-periodic oscillations (HFQPOs) at 66 Hz in the RXTE data of the black hole candidate IGR J17091–3624, a system whose X-ray properties are very similar to those of microquasar GRS 1915+105. The centroid frequency of the strongest peak is ~ 66 Hz, its quality factor above 5 and its rms is between 4 and 10%. We found a possible additional peak at 164 Hz when selecting a subset of data; however, at 4.5σ level we consider this detection marginal. These QPOs have hard spectrum and are stronger in observations performed between September and October 2011, during which IGR J17091–3624 displayed for the first time light curves which resemble those of the γ variability class in GRS 1915+105. We find that the 66 Hz QPO is also present in previous observations (4.5σ), but only when averaging ~ 235 ksec of relatively high count rate data. The fact that the HFQPOs frequency in IGR J17091–3624 matches surprisingly well that seen in GRS 1915+105 raises questions on the mass scaling of QPOs frequency in these two systems. We discuss some possible interpretations, however, they all strongly depend on the distance and mass of IGR J17091–3624, both completely unconstrained today.

Subject headings: X-rays: binaries — binaries: close — stars: individual (IGR J17091–3624, GRS 1915+105) — Black hole physics

1. INTRODUCTION

One of the strongest motivations for studying Low-mass X-ray binaries (LMXBs) has been the aim to use these systems as probes of fundamental physics. It has been argued that the study of high frequency (40–450 Hz) quasi-periodic oscillations (HFQPOs) found in LMXBs containing a stellar mass black hole (BH) is one of the most promising tools to do so. The HFQPOs are the fastest phenomenon observed in these systems and their high frequency suggests that they are produced in the innermost region of the accretion flow near the BH event horizon. Once the processes involved in their formation are firmly understood, they will give a wealth of information on BH mass and spin as well as the structure of strongly curved space-time (e.g., Nowak et al. 1997; Wagoner 1999; Stella et al. 1999; Wagoner et al. 2001; Abramowicz & Kluźniak 2001; Kato 2001; Rezzolla et al. 2003).

The frequency of the HFQPOs usually occur at specific values, different in each source. In a few cases, pairs of QPOs have been detected. The highest frequency appears to scale inversely proportional to the BH mass (e.g., McClintock & Remillard 2006; Belloni et al. 2006b). HFQPOs are weak, transient, and energy dependent, and are mostly detected only at high count rates. In some cases they are found just above detection levels, so there is considerable uncertainty about their exact properties. However, typically the quality factor Q ranges between less than 2 and a few tens, and amplitudes are between 0.5 and 5% rms (depending on the source and the energy range used).

Twin QPOs at a stable 300 Hz and 450 Hz (Strohmayer 2001a) have been observed in the BH GRO J1655–40; at 240 and 160 Hz in H1743–322 (Homan et al. 2005) and at 188 and 268 Hz in XTE J1550–56 (note however, that in this case it is not clear how stable the frequency of these QPOs is, see Remillard et al. 1999; Homan et al. 2001; Miller et al. 2001). Single QPOs or peaked noise (i.e. when $Q \lesssim 2$) features at a rather stable frequency have been detected in XTE J1650–500 (~ 250 Hz, see, e.g., Homan et al. 2003), 4U 1630–47 (variable frequency, see Klein-Wolt et al. 2004) and XTE J1859+226 (~ 180 Hz, see, e.g., Cui et al. 2000).

The remaining BH which shows HFQPOs is the peculiar system GRS 1915+105, which is a 33.5 days orbital period binary system harboring a $14.0 \pm 4.4 M_{\odot}$ BH (Greiner et al. 2001; Harlaftis & Greiner 2004). At a distance of ~ 12.5 kpc (Mirabel & Rodríguez 1994), it is very often at Eddington or super-Eddington luminosity (e.g., Done et al. 2004). Until recently, GRS 1915+105 has been unique in that its X-ray light curves exhibit more than a dozen different patterns of variability usually called “classes” (which are referred to with Greek letters), most of which are high amplitude and highly-structured (e.g., Belloni et al. 2000). Most of this structured variability occurs on timescales of seconds or longer, and it is thought to be due to limit cycles of accretion and ejection in an unstable disk (e.g., Belloni et al. 1997; Mirabel et al. 1998; Tagger et al. 2004; Neilsen et al. 2011).

GRS 1915+105 has HFQPOs at the rather low frequencies of ~ 40 Hz (Strohmayer 2001b) and ~ 67 Hz (Morgan et al. 1997) compared with the rest of the BH systems; however, as in the case of GRO J1655–40 and H1743–322, the QPO frequencies remain almost constant as the X-ray flux changes (any change in the frequency of the ~ 40 Hz oscillation during the sequence of observations was $\lesssim 1\%$; the frequency of the 67 Hz oscilla-

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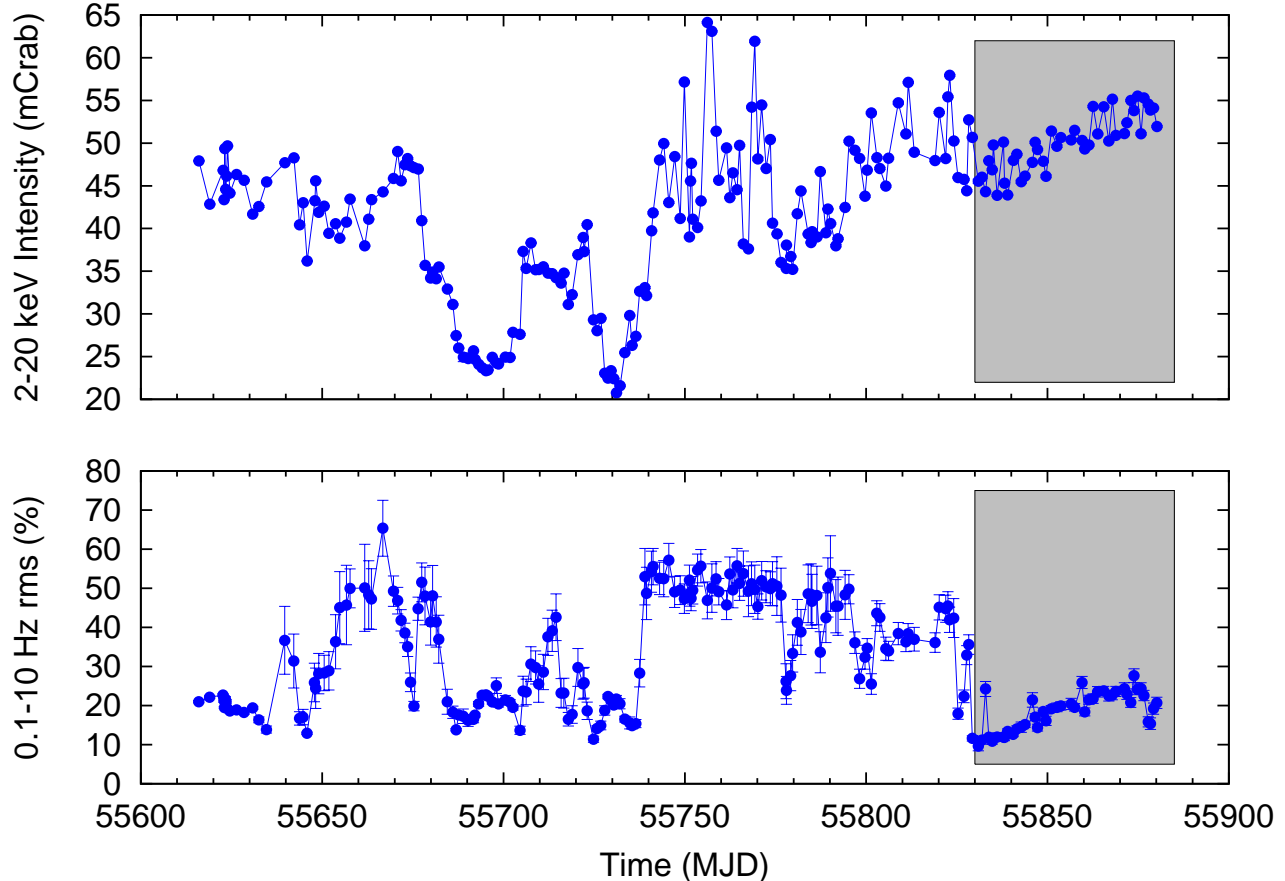


FIG. 1.— *Upper panel:* Crab-normalized 2-20 keV intensity of the full outburst of IGR J17091–3624 sampled with RXTE. *Lower panel:* 0.01-10 Hz fractional rms amplitude (2-60 keV) range. Points are per observation. The grey area marks the period of fast γ class of variability (e.g., Belloni et al. 2000). The average power spectra of all observations in this region is shown in Figure 2.

tion varies by only a few percent as the X-ray flux varies by a factor of several), suggesting a common origin between systems. Belloni et al. (2001) reported on the detection of QPOs at ~ 27 Hz; given the weakness of the signal Belloni et al. (2001) could not determine whether the ~ 27 Hz was related to the ~ 67 Hz QPO (at the time of Belloni et al. 2001, the ~ 40 Hz QPO was not yet reported); however, they were able to conclude that the presence/absence of HFQPOs is intimately linked to the slower oscillations and variations that happen on timescales longer than seconds. An additional peak at ~ 170 Hz was also found after applying a very specific class-count rate-hardness selection (Belloni et al. 2006b); however, this barely significant peak is very broad, with a Q value of ~ 2 .

If the frequency of the HFQPOs depends on the mass and/or spin of the BH, one would expect (as observations appear to suggest), that different systems with different parameters should show QPOs at different frequencies. The recent discovery of a BH (IGR J17091–3624) which shows very similar high amplitude and highly-structured variability to that seen in GRS 1915+105 (see Altamirano et al. 2011c, and references therein) opened a new window of opportunities to understand the physical mechanism that produces the highly structured X-ray variability and its relation with much faster (sub-second) variability.

IGR J17091–3624 has been seen active in 1994,

1996, 2001, 2003, 2007 and 2011 (Revnivtsev et al. 2003; in’t Zand et al. 2003; Capitanio et al. 2006; Kuulkers et al. 2003; Capitanio et al. 2009; Krimm et al. 2011). Only in the recent 2011 outburst IGR J17091–3624 started to show the high amplitude and highly-structured variability (Altamirano et al. 2011d,a,b,c; Pahari et al. 2011) typical of GRS 1915+105. In the context of the variability classes defined by Belloni et al. (2000) for GRS 1915+105, Altamirano et al. (2011c) found that IGR J17091–3624 shows the ν , ρ , α , λ , β and μ classes as well as quiet periods which resemble the χ class, all occurring at 2-60 keV count rate levels which can be 10-50 times lower than observed in GRS 1915+105. Altamirano et al. (2011c) also found that the difference in flux combined with the circumstance that currently neither the distance to IGR J17091–3624 nor the mass of its compact object are known lead to the conclusion that either all models requiring near Eddington luminosities for GRS 1915+105-like variability fail, or IGR J17091–3624 lies at a distance well in excess of 20 kpc or, it harbors one of the least massive BHs known ($< 3M_{\odot}$).

The similarities and differences between IGR J17091–3624 and GRS 1915+105 raises the question of at what frequency should we observe the HFQPOs in IGR J17091–3624. Assuming $1/M$ scaling, and the possibility that IGR J17091–3624 has a mass which is a factor of ~ 5 smaller than GRS 1915+105, then the HFQ-

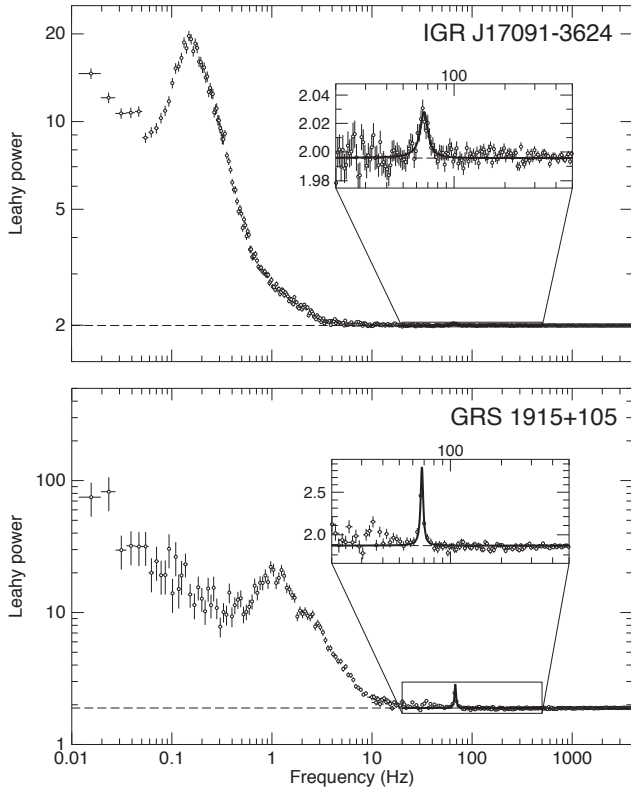


FIG. 2.— *Upper panel:* Averaged power spectra of all observations of IGR J17091-3624 marked by the grey area in Fig. 1 (for a total of ~ 74 ksec of data). *Lower panel:* Average power spectra of a single observation (ObsID: 80701-01-28-01) of GRS 1915+105. Both plots show the typical γ variability class power spectra, with a strong broad bump at low frequencies. Insets show a zoom to the $\sim 65 - 67$ Hz QPO.

POs in IGR J17091-3624 should be at a frequency significantly higher than the ~ 40 Hz and ~ 67 Hz seen in GRS 1915+105. Finding similar HFQPO frequency between sources would imply that the frequency does not depend on the mass or that IGR J17091-3624 lies at a distance well in excess of 20 kpc.

Triggered by this question, we searched all the *Rossi X-ray Timing Explorer* (RXTE) available data of IGR J17091-3624 for the presence of QPOs at frequencies higher than the ~ 7 -10 Hz reported by Altamirano et al. (2011c). In this Letter we report the discovery of a highly significant QPO at ~ 65 Hz, and a marginally detection of a QPO at ~ 165 Hz and briefly discuss the implication of our detections.

2. OBSERVATIONS AND DATA ANALYSIS

IGR J17091-3624 was observed with the Proportional Counter Array (PCA; Jahoda et al. 2006) on-board RXTE almost daily since the outburst began in February 2011 until October 15th, 2011, when RXTE could not point to IGR J17091-3624 any more due to visibility constraints. A total of 228 observations, covering ~ 280 days, sample the 2011 part of the current outburst (At the moment of submission it is not known whether the source is still active or not). In this work we do not use data taken between MJD 55600 and 55614 (14 observations), given that these observations were affected by a bright source in the field of view (e.g., Altamirano et al. 2011c).

We use the 16-s time-resolution Standard 2 mode data

to calculate the Crab-normalized average per observation 2-20 keV intensity (see, e.g., Altamirano et al. 2008, and references therein for details on the method). Power spectra and light curves were produced from the PCA using standard techniques (e.g., Belloni et al. 2000; Altamirano et al. 2008). For the Fourier timing analysis we used data in the 2-25 keV range (absolute channels 5-60) from the Good Xenon mode.

To fit the high-frequency (> 10 Hz) part of power spectra, we used one or two Lorentzian functions plus a power-law when needed. We give the frequency of the Lorentzians in terms of characteristic frequency $\nu_{max} = \sqrt{\nu_0^2 + (FWHM/2)^2} = \nu_0 \sqrt{1 + 1/4Q^2}$ (Belloni et al. 2002). For the quality factor Q we use the standard definition $Q = \nu_0/FWHM$. $FWHM$ is the full width at half maximum and ν_0 the centroid frequency of the Lorentzian. The strength of the QPOs are given in terms of fractional rms amplitude.

3. RESULTS

3.1. Outburst evolution

In the upper and lower panel of Fig. 1 we show the average 2-20 keV intensity for each observation and the 0.01-10 Hz rms amplitude, respectively. During the 265 days period, IGR J17091-3624 has been at an average intensity between 20 and 65 mCrab. (Note that during single flares or heartbeats the source was much brighter). The rms amplitude also varied significantly, where IGR J17091-3624 underwent periods of very low ($\sim 10\%$) and very high ($> 60\%$) amplitude. Figure 1 shows that there is no clear correlation between intensity and rms amplitude. A similar study of GRS 1915+105 shows the same (this will be reported elsewhere).

3.2. High frequency QPOs

At first we searched each observation power spectrum for indications of QPOs at higher frequency than 10 Hz and at a significance larger than 3.5σ . We found a clear detection (4.7σ , single trial) of a QPO at $\nu = 64.8 \pm 1.7$ Hz, $Q = 4.8 \pm 1.7$ and rms amplitude of $10 \pm 1\%$ (2-25 keV, ObsID: 96420-01-36-03, MJD 55865.5). We also found that in the period MJD 55830-55880 many power spectra revealed power excesses in the 60-70 Hz range. To further investigate this, we added all data in this period, which corresponds to the low-variability period marked with a grey area in Fig. 1. In the upper panel of Fig. 2 we show that the resulting power spectrum is clearly dominated by a strong feature at ~ 0.18 Hz, but also shows an 8.5σ QPO at 66.5 ± 0.5 Hz ($Q = 7.8 \pm 1.5$; $4.9 \pm 0.2\%$ rms amplitude).

Different sub-selections on time and intensity of these data lead to significant changes in Q , amplitude and significance, but not in frequency. This suggests that the 66 Hz QPO is not always present, similar to what occurs in GRS 1915+105. In several of our sub-selections we saw an excess of power in the 150-200 Hz range. In the left panel of Fig. 3 we show the result of averaging all observations after MJD J55841. The QPO at ~ 66 Hz (9σ significant, $Q = 6 \pm 1$, $6.4 \pm 0.4\%$ rms amplitude) is accompanied with a QPO at 164 ± 10 Hz ($\sim 4.5\sigma$, $Q = 2.6 \pm 1.3$, $6.6 \pm 0.8\%$ rms amplitude); In the inset we show the rms amplitude vs. energy of the 66 Hz QPO; its amplitude increases with energy from $\sim 5\%$ at 3 keV,

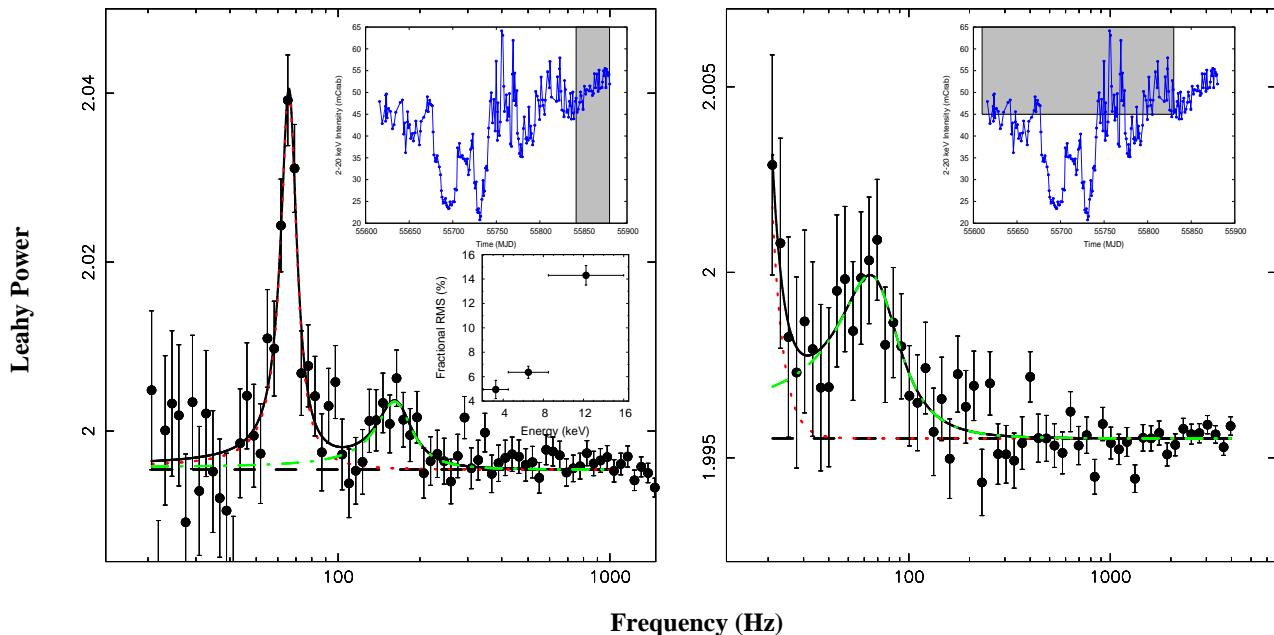


FIG. 3.— *Left panel:* Average power spectrum of all observations after MJD 55841 (for a total of 48 ksec). The 66 ± 0.5 Hz QPO is 9σ significant, while the $\sim 164 \pm 10$ Hz is 4.5σ . Lower inset shows the rms amplitude vs. energy for the 66 Hz QPO. *Right panel:* Average power spectrum of all observations performed before MJD 55830, when the average intensity of IGR J17091-324 was higher than 46 mCrab (corresponding to ~ 100 cts s^{-1} PCU $^{-1}$; we used a total of ~ 235 ksec). Note the difference the y axis scales. The broad ($Q=1$) QPO at 70 ± 6 is 4.5σ significant. In both panels we used data in the 2-25 keV range. Insets on the top: light curves marking with grey area the data used to produce each power spectrum.

to $\sim 14\%$ at 13 keV. The 67 Hz QPO in GRS 1915+105 also has a hard spectrum, although less extreme than this one Morgan et al. (1997). The low S/N did not allow a similar analysis for the 164 Hz QPO.

We also explored whether the 65 Hz QPO is also present before MJD 55830 which is not detected due to the low-statistics. Averaging all data in this period led to a broad feature at ~ 60 -80 Hz whose parameters were unconstrained. When we selected only high count rates (> 110 cts/sec/PCU), we detected a 4.5σ broad ($Q = 1.2 \pm 0.5$) feature at 70 ± 6 Hz ($4.4 \pm 0.4\%$ rms amplitude). We show our best fit in the right panel of Fig. 3.

We did not detect any QPO at 40 Hz nor 27 Hz as seen in GRS 1915+105. This is not surprising, as those QPOs can be weaker and complex data selection might be needed to find them (e.g., Strohmayer 2001b; Belloni et al. 2001).

3.3. The low-variability period MJD 55830-55880

The period MJD 55830-55880 (where the 66 Hz QPO is strongest, see Section 3.2) corresponds to an interval of relative low (10-30%) rms amplitude. The 1-sec light curves during this period are relatively flat, apart from quasi-periodic oscillations with a typical time scale of 10 s and/or the presence of sharp dips with a typical duration of a few seconds. In the upper panel of Fig. 4 we show a representative lightcurve during this period.

When compared with the GRS 1915+105 variability classes defined by Belloni et al. (2000), the IGR J17091-3624 light curves during MJD 55830-55880 are reminiscent of the γ class. As a comparison, in the lower panel of Fig. 4 we plot a representative γ class data-segment for GRS 1915+105 (for the full light curve, see Figs. 2f and 15b,d in Belloni et al. 2000). A comparison between power spectra between the IGR J17091-3624 and

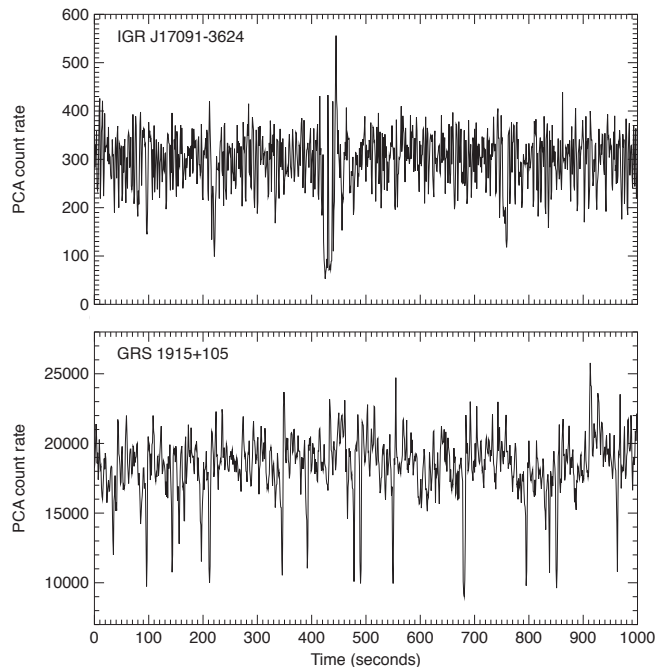


FIG. 4.— Upper and lower panel show 1 sec bin light curves of IGR J17091-3624 (subset of ObsID 96420-01-37-04) and GRS 1915+105 (subset of observation 20402-01-39-00, see also Belloni et al. 2000), respectively, during the γ variability class.

GRS 1915+105 is shown in Fig. 2.

4. DISCUSSION

We discovered the presence of a HFQPO in the RXTE data of the IGR J17091-3624, a system whose X-ray properties are very similar to those of GRS 1915+105. The centroid frequency of the strongest peak is ~ 66 Hz, its quality factor above 5 and its rms is between 4 and 10%. We found a possible additional peak at 164 Hz

when selecting a subset of data; however, we consider this detection marginal.

The HFQPOs are detected during a period where IGR J17091–3624 is in the γ variability class (Belloni et al. 2000). Altamirano et al. 2011c reported observations until MJD 55800 where so far IGR J17091–3624 was seen in at least the ν , ρ , α , λ , β , μ and χ classes. The fact that now we also identified the γ class probably means that IGR J17091–3624 is still evolving between classes.

The frequency of the 66 Hz QPO in IGR J17091–3624 is surprisingly similar to that of the main HFQPO in GRS 1915+105 (65–69 Hz, see Morgan et al. 1997). In addition, the frequency of the 4.5σ significant broad feature at 164 ± 10 Hz in IGR J17091–3624 also matches that of a similar broad feature found at 170 Hz in GRS 1915+105 (Belloni et al. 2006a). The circumstance that currently neither the distance to IGR J17091–3624 nor the mass of its compact object are known led Altamirano et al. (2011c) to the conclusion that either all models requiring near Eddington luminosities for GRS 1915+105-like variability fail, or IGR J17091–3624 lies at a distance well in excess of 20 kpc or, it harbors one of the least massive BHs known ($< 3M_{\odot}$). The surprisingly match between the ~ 70 Hz and ~ 170 Hz frequency therefore raises more questions than answers.

The frequencies of dynamical motions near compact objects are thought to scale with mass (e.g., van der Klis 2006). The slower highly-structured low-frequency variability seen in GRS 1915+105 as compared with IGR J17091–3624 supported the idea that the later was less massive (Altamirano et al. 2011c). However, the fact that the HFQPOs occur at the same frequency could be at odds, meaning that either the frequency of the HFQPOs or the highest-frequency of the ‘heartbeats’ in these two sources scale with mass, or that none of them do, or that they both do thanks to a difference in BH spin.

If the 67 Hz HFQPOs frequency scales with mass (assuming same mass, same spin), then either IGR J17091–3624 is further than 20 kpc or it is close, in which case all models requiring near Eddington luminosities for GRS 1915+105-like variability fail (Altamirano et al. 2011c). Under the assumption that the centroid frequencies represent that of a Keplerian circular motion at the inner-most stable orbit (ISCO), then at first approximation (e.g., Kluzniak et al. 1990) no solution is possible for the 67 Hz QPOs independently of the spin, unless either the HFQPOs are not produced at the ISCO or the mass of both BHs is significantly higher than the $\sim 14M_{\odot}$ estimated for GRS 1915+105. The 160–170 Hz broad QPOs found in both in IGR J17091–3624 (this Letter) or GRS 1915+105 would be consistent with a $14\text{--}20M_{\odot}$, but only if the spin parameter (a/M_{BH}) in these systems is significantly lower than 1 (i.e., at odds with the reported $a/M_{BH} \simeq 1$ for GRS 1915+105, e.g., McClintock et al. 2006; Blum et al. 2009).

In the framework of the Relativistic Precession Model (RPM, Stella et al. 1999), and relaxing the assumption on equal spin, we can identify the higher frequency (160–170 Hz) as representing a Keplerian motion at a certain radius and, the lower frequency (66 Hz) as the relativistic periastron precession at the same radius (notice that this radius must be larger than the ISCO, where the two frequencies are the same). To test this identification, we searched for the combinations between spin parameter and BH mass which allow a solution. We find solutions for masses ranging between $7 M_{\odot}$ (for $a/M_{BH} = 0$) and $19 M_{\odot}$ (for $a/M_{BH} = 1$), the latter consistent with the $14.0 \pm 4.4 M_{\odot}$ and $a/M_{BH} \simeq 1$ reported for GRS 1915+105 (Greiner et al. 2001; Harlaftis & Greiner 2004; McClintock et al. 2006; Blum et al. 2009). This identification implies that IGR J17091–3624 could be considerably less massive than GRS 1915+105 (and coincidentally have a much lower spin than GRS 1915+105), explaining in this way why the highest frequency of the ‘heartbeats’ is significantly higher in IGR J17091–3624 than in GRS 1915+105 (Altamirano et al. 2011c). We note that in the framework of the Relativistic Precession Model the 41 Hz frequency would be unexplained. Solutions to the 41,67 Hz pair for GRS 1915+105 are possible, but only for masses larger than $25M_{\odot}$ and considering no spin (i.e. $a/M_{BH} = 0$).

If the HFQPOs frequency *does not* scale with mass, then it is intriguing why their HFQPOs frequencies are the same in these two sources. One possibility is that the 67 Hz HFQPOs are different from the HFQPOs seen in other sources (e.g., van der Klis 2006), and that their frequency is instead related with the physical process that produces the highly-structured low-frequency variability (only seen) in these two sources. If true, this could have major implications on works that use the ~ 67 Hz HFQPO in GRS 1915+105 as a standard to estimate the mass of galactic and/or super massive BHs (e.g. Middleton & Done 2010).

Our results add another HFQPO to the small number already known. Its properties are not different from the others, in particular its elusiveness. There are thousands of observations of more than 20 black-hole transients in the RXTE archive, but only very few significant peaks have been found. As RXTE will cease operations in 2012 January, this sample is not going to be increased until the Indian astronomical mission ASTROSAT is launched, while a major step forward will only come with the next generation of X-ray instruments (e.g. LOFT, see Feroci et al. 2011).

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